Predicting the runout behaviour of debris flows and debris avalanches

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Debris flows and debris avalanches are two of the most destructive of all landslide phenomena. Potential events often threaten populated areas in mountain foothills and valleys. Delimiting the extent of endangered areas and estimating potential damage are essential steps in reducing the hazard by means of development restrictions or defensive structures. Such steps require accurate prediction of the runout behaviour of these types of mass movement. This in turn requires an understanding of the mechanics of motion.

Current and past research into the runout behaviour and mechanics of mass movement can generally be grouped into two categories. The first includes empirical models aimed at providing practical tools for predicting the distribution of debris. The second category includes mathematical models, which describe the physical behaviour of mass movement. Models in each category can be applied to runout prediction. This presentation includes a review of models presently available and the introduction of a new method of prediction currently being developed by the authors. We suggest that our model can bridge the gap between the two categories to provide a means for practical runout prediction.

Heim [1932] was the first to note a relationship between the volume of rock avalanches and their travel distance. Scheidegger [1973] formalised this relationship by defining a correlation between landslide volume and the ratio of the total fall height, H, to the total runout distance, L, based on data from 33 prehistoric and historic rock avalanches. The ratio of H/L, termed the effective friction angle, has been considered by many authors as a measure of mobility. Li [1983] also demonstrated a correlation between rockslide volume and H/L, as well as between rockfall volume and deposition area covered by the fallen mass, referred to as the area-volume method of runout prediction. Correlations have also been made between volume and total length of deposit [Li 1983, Davies 1982].

Hs [1975] presented evidence to support Heim's contention that rock avalanches flow rather than slide, resulting in spreading of the debris lobe during deposition. Based on this theory, he introduced the excessive travel distance as an alternative measure of mobility. Nicoletti [1991] presented a modified version of the Hs model and studied the local geomorphic controls on the shape and motion of rock avalanches, in addition to providing a comparative review of empirical methods of prediction.

All of the empirical methods described above have been derived from data for rock avalanches of volumes greater than 0.1 to 1 Mm$^3$. Thus, they do not provide methods for predicting the runout behaviour of debris flows and debris avalanches or for any failures with volumes less than 0.1 to 1 Mm$^3$. Cannon [1989], however, found that linear relations exist between travel distance and initial volume of material for debris flows. Her approach was elaborated by Fannin and Wise [1996]. In addition, Corominas [1996] showed a linear correlation between volume and angle of reach for all types of failures. He found that all kinds of mass movement show a continuous decrease in angle of reach with increasing volume starting from magnitudes as small as 10 m$^3$. This correlation contained a great deal of scatter, which he attributed mainly to path obstructions.
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While empirical methods provide approximate predictions of the runout distance, calibration of these models has been limited. Furthermore, for application to hazard zoning and risk assessment, it is necessary to predict not only the runout distance, but also the deposit thickness and the discharge and velocity at critical locations. Several mathematical models describing the mechanics of motion of debris flows and debris avalanches have been presented in the literature. Most models involve the application of a selected rheology within the framework of an unsteady flow model.

Rheological constitutive relationships applied to mass movement modelling in the past have usually been one of either Newtonian flow [e.g. Curry 1966], Bingham flow [e.g. Sousa and Voight 1991] or dilatant grain-flow [e.g. Takahashi 1991]. Some researchers have applied the Coulomb friction model in various ways to debris flows and debris avalanches [Hung 1995, Iverson 1997]. Sassa [1998] proposed a two-parameter friction model for landslides, which includes the apparent sliding friction and a pore-pressure ratio within the moving mass. The applicability of the Voellmy rheology to debris flows [Voellmy 1955] has been tested by Rickenmann and Koch [1997], who found that models using a Newtonian turbulent or Voellmy fluid yielded the best simulations of channelised flows.

Some of the most recent solution methods involve the application of a more complex combination of rheologies. Iverson [1997] describes the physics of debris flows based on the equations of motion for the flow of dry granular masses. The model is essentially a frictional one, which includes longitudinally varying internal and boundary forces as well as pore pressure. Hungr (in press) applied a combined friction/viscous fluid rheology with variable viscosity to a uniformly progressive flow model for debris flows. More detailed reviews of the existing mathematical runout models have been presented by Johnson and Rodine [1984], Takahashi [1991], Hung [1995] and Iverson [1997].

No single rheological model appears to be valid for all debris flows and debris avalanches, or possibly even for one isolated event. Detailed mechanistic models are currently too complex and uncertain to provide practical prediction. Furthermore, calibration of existing numerical models with real-life events is very limited; thus, their predictive capabilities remain poor. There remains a need for a practical tool which provides an accurate and robust method of runout prediction of rapid mass movement.

A simple numerical model for the dynamic analysis of unsteady flow [Hung 1995] is currently being systematically calibrated through the back-analysis of a variety of debris flow and debris avalanche case histories. Data has been collected from several regions including Hong Kong and British Columbia [Ayotte and Hung 1998, Jakob et. al. 1999]. The model allows the selection of a rheological relationship which defines the flow resistance. Calibration is constrained not only by the runout distance, but also by the velocity at various locations in the runout path as well as the distribution of debris, including deposit area and thickness.

Debris flows and avalanches are complex phenomena, involving highly unsteady motion of heterogeneous material ranging from water and slurries to boulders and timber remains. It is therefore very difficult to find a unique constitutive relationship applicable to all parts of the flow. This work follows the simplified concept of “equivalent fluid”, suggested by Hung (1995). The dynamic analysis is carried out using a specific rheological model, selected by trial-and-error so as to produce external flow behaviour consistent with actual cases. On a micro- or mesoscopic scale, the model may represent only parts of the flow and only at certain times during the event. It should, however, approximate the bulk behaviour of the event at the macroscopic scale. It cannot be claimed that the model is a good representation of the rheological character of debris flow material. Nevertheless, it provides a practical means of predicting the runout behaviour.
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Results to date indicate that most debris avalanches on open slopes can be simulated satisfactorily using a friction model with pore-pressure conditions that are intermediate between fully drained and liquefied. The friction model tends to predict somewhat exaggerated velocities and deposits the bulk of the debris proximally with gradual thinning away from the source (Figure 1a). Channelised debris flows involving the dilution of debris by water and/or the entrainment of liquefied saturated material appear to conform best to a friction-turbulent (Voellmy) model. The Voellmy model generally results in lower velocities, uniformly distributed deposits, and moderately long deposit areas with accumulation on the flatter parts of the slope (Figure 1b).

Figure 1: Model debris deposit of a small debris flow: a comparison of the cross-sectional distribution using a. the friction rheology, and b. the Voellmy rheology.

Through the back-analysis of several case histories, relationships between slope properties and model rheologies are emerging. These relationships will allow the definition of a typological classification system based on pre-failure slope properties. This classification system will provide criteria for the selection of a rheological model, which will in turn provide a reliable method for prediction of the runout characteristics using the dynamic model.

References


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Biographical Note:
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Dana Ayotte holds a B.Sc. in Mechanical Engineering from Queen's University and a M.S. in Mechanical Engineering from M.I.T. She is currently a Ph.D. candidate in Engineering Geology in the department of Earth and Ocean Sciences at the University of British Columbia.